IMS CALIBRATION IN NORTH AMERICA AND NORTHWESTERN EURASIA UTILIZING 3-D CRUSTAL AND UPPER MANTLE VELOCITY MODELS TO REFINE LOCATION OF REGIONAL SEISMIC EVENTS

Russian Federation / United States Calibration Working Group
Contact Person: Vladislav Ryaboy

Center for Monitoring Research

Sponsored by The Defense Threat Reduction Agency
Arms Control Technology Division
Nuclear Treaties Branch
Contract No. DSWA01-98-C-0032

ABSTRACT

This work was performed within the United States/Russian Federation Joint Research Program of Seismic Calibration of the International Monitoring System (IMS) in Northern Eurasia and North America. The parties to this program are the Nuclear Treaty Programs Office (NTPO), Department of Defense (DOD), USA and the Special Monitoring Service (SMS) of the Ministry of Defense (MOD), Russian Federation. A RF/US working group (WG) has been established to coordinate the joint research program, and the current membership is given below. The main objective of the calibration effort is to improve the IMS location accuracy of the regional seismic events within North America and Northwestern Eurasia (west of the Ural Mountains) using calibration datasets exchanged between the US and RF to derive Source-Specific Station Corrections (SSSCs) from 3-D crustal and upper mantle velocity models. 3-D modeling software developed by P. Firbas was used to compute SSSCs from 3-D crustal and upper mantle models for Pn, Sn, and Pg phases within North America and for Pn within Northwestern Eurasia. We described the 3-D velocity models used for calculations of the Pn and Pg travel times at the 21st Seismic Research Symposium (Las Vegas, Nevada, 1999) and at the 2nd Workshop on IMS Location Calibration in Oslo, Norway. The 3-D velocity models for Sn-waves were calculated from the Pn model using the relationship for Vp/Vs vs. depth from the AK-135 model of Kennett et al. SSSCs were calculated for the regional phases Pn, Pg, and Sn out to distances of 20 degrees, 10 degrees, and 20 degrees, respectively, for 22 IMS stations and 4 additional stations in North America and for 26 IMS stations and 9 additional stations in Northwestern Eurasia.

These SSSCs, with their estimated modeling errors, were applied to relocate 9 large chemical and nuclear explosions with known locations and origin times detonated within various tectonic provinces of Northwestern Eurasia and an independent set of 10 chemical explosions detonated within different regions of North America. The validation results are preliminary, but we generally find that the model-based SSSCs produce significantly improved location accuracies and reduced confidence ellipses for GT0 and GT2 events in the cases where it can be shown that the analysis data are accurate. Results of relocation experiments for selected events located in different regions of North America and Northwestrn Eurasia clearly indicate that our model-derived SSSCs and estimated modeling errors improved the average location accuracy compared to the IASPEI-91 tables from 25.9 km to 5.7 km for North America and from 28.1 km to 9.3 km for Northwestern Eurasia, and decreased the 90% error ellipse area for all events from 3,840 km^2 to 817 km^2 and from 6,512 km^2 to 1,284 km^2, respectively. The error ellipses contained the ground-truth locations for all events we tested at the 90% confidence level. Our study demonstrates the promise of the application of the 3-D travel-time modeling approach for deriving bias corrections to improve regional seismic event locations.

The RF members of the WG: Colonel Vyacheslav Gordon (chairman), Colonel Vitaly Shishkov, Lt. Colonel Dmitry Bobrov, and Dr., Prof. Marat Mamsurov. The US members of the WG: Dr. Anton Dainty (chairman), Dr. Douglas Baumgardt, Mr. John Murphy, Dr. Robert North, and Dr. Vladislav Ryaboy.

Key Words: location, calibration, IMS, 3-D crustal and Upper mantle velocity models, Pn, Sn, and Pg waves.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE
IMS Calibration In North America And Northwestern Eurasia Utilizing 3-D Crustal And Upper Mantle Velocity Models To Refine Location Of Regional Seismic Events

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Russian Federation / United States Calibration Working Group,Arlington,VA,22209

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) held in New Orleans, Louisiana on September 13-15, 2000, U.S. Government or Federal Rights.

14. ABSTRACT
See Report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVE

This paper presents results from the Russian Federation / United States Joint Research Program of Seismic Calibration of the International Monitoring System in Northern Eurasia and North America during 1999-2000. The participants in this program are the Nuclear Treaty Programs Office, Department of Defense, USA, and the Special Monitoring Service of the Ministry of Defense, RF. To date the Joint Program has focused on collection and interpretation of data from large chemical and nuclear explosions with known location and origin time to improve regional seismic event location by the IMS in western areas of Northern Eurasia and North America.

A location accuracy of 1000 km^2 in continental areas is desirable for the IMS based on the limitation of On-Site Inspections to this area under the CTBT. However, this accuracy often cannot be achieved with globally averaged travel-times because of large variations of travel-times of regional phases. These travel-time variations are mainly caused by lateral velocity variations in the crust and upper mantle. To achieve the CTBT goal of 1000 km^2 location accuracy the IMS has to be calibrated, i.e., travel-times of seismic waves used in the location must take into account the 3-D structure of the Earth (Firbas, Peshkov, and Ryaboy, 1997). Regional seismic event location accuracy is critically dependent on the joint contribution of several factors, including seismic network configuration, errors in arrival time measurements, phase (mis)identification, and accuracy of reference travel-time curves based on crustal and upper mantle velocity structure. Seismic event locations based on regional 1-D velocity models can have errors caused by travel-time variations within different major tectonic provinces and by ray paths crossing boundaries between tectonic provinces with different crustal and upper mantle velocity structures. Seismic event locations based on 3-D velocity models have the potential to overcome these limitations. The main objectives of this paper are the following:

- Regionalization of western areas of Northern Eurasia and North America based on tectonic and seismic data.
- Seismic travel-time data collection and analysis.
- Deriving 3-D velocity models and source-specific station corrections (SSSCs).
- Regional seismic event relocation to demonstrate the improvement in location accuracy.

RESEARCH ACCOMPLISHED

The 3-D approach for the IMS calibration includes the following main steps:

- Regionalization based on tectonic data, travel-times, and crustal and upper mantle velocity structures;
- Collection and analysis of Pn travel-times;
- Collection and analysis of 1-D crustal and upper mantle velocity-depth sections;
- Development of a 3- crustal and upper mantle velocity model;
- Computation up to distance of 20 degrees of Source-Station Specific Corrections (SSSCs) for seismic stations using the 3-D crustal and upper mantle velocity model for the Pn wave (Northern Eurasia, western part) and for Pn, Sn, and Pg waves (North America);
- Regional seismic event relocation to demonstrate the improvement in location accuracy.

These steps are described further in this paper.

Tectonic maps of North America and Northern Eurasia were taken as a starting point for delineating various tectonic provinces. These maps were simplified and digitized to allow more reliable interpolation and comparison of seismic data (travel times of seismic waves, crustal and upper mantle velocity models, location of seismic stations and seismic events) for different tectonic provinces (Figure 1, top; Figure 2, top) and to help create a 3-D starting velocity model of the crust and upper mantle for North America and Northern Eurasia. Detailed seismic studies of the Earth's crust and upper mantle have been carried out in most regions of Northern Eurasia and North America and published in numerous reports, papers, and monographs (e.g. Pakiser and Mooney, 1989; Pavlenkova 1996; Romanowicz, 1979; Van der Lee and Nolet, 1997; and many other published works). The crust and upper mantle velocity structure varies most strongly between western areas of North America and the Pre-Cambrian platform.When crossing the boundary from west to east between these tectonic provinces, values of mean velocity in

the crust, Moho depth, and Pn velocity increase from approximately 6.2-6.3 km/s, 30-35 km, and 7.7-7.9 km/s to 6.5-6.6 km/s, 40-50 km, and 8.1-8.2 km/s, respectively. The crustal thickness (Moho depth) within Northern Eurasia varies from 55-60 km beneath the Ural mountains to 32-35 km beneath the North Caspian sedimentary basin. Crossing the boundaries between the Pre-Cambrian platforms (East-European and Siberian) and the young Paleozoic platforms (Timan-Pechora and West-Siberian platforms) is typically accompanied by a decrease of crustal thickness from approximately 45-50 km to 35-40 km, respectively. In general the crustal thickness decreases towards the Arctic ocean. Pn velocity within Northern Eurasia varies from approximately 7.8-8.0 km/s to 8.4 km/s and greater. The largest values of Pn velocity are found beneath the East-European and Siberian Pre-Cambrian platforms (8.1-8.4 km/s and greater.

Eight nuclear and large chemical explosions with known locations and origin time in North America (Figure 1, top) and 24 nuclear and large chemical explosions in Northern Eurasia (Figure 2, top) were selected to serve as events for location calibration, i.e., the travel-time corrections were derived from seismic recordings of them. Analysis of explosion seismology observations shows that the Pn travel-time variations are caused by lateral inhomogeneities of the Earth's crust and upper mantle velocity structure, on both large and small scales. In the development of our 3-D models of North America and Northern Eurasia we started fitting the large scale anomalies first. Where necessary, we continued to fit smaller scale anomalies. Both types of anomalies had to be taken into account to achieve accurate location of regional seismic events as required by the IMS calibration task. The computer program "sssc" (Firbas, 2000) was used to compute SSSCs for Pn, Pg, and Sn travel-times up to distance 20 deg, 8 deg, and 20 deg, respectively, from the 3-D earth velocity model. The goal was to define 3-D crustal and and upper mantle velocity models capable of predicting Pn travel-times with an accuracy of approximately 1.0-1.5 sec (r.m.s.). The simplest 3-D velocity models were sought from a family of 3-D models that simultaneously fit the observed Pn travel-times for all calibration events. Figure 1 (bottom) and Figure 2 (bottom) show the upper mantle regionalization for North America and Northern Eurasia, and numbers on these Figures refers to numbers on the velocity models of Figure 3 (top) and Figure 3 (bottom), respectively.

Long-range seismic profile observations can be used very effectively for IMS calibration. Figure 4 (top) and Figure 4 (bottom) compare observed and calculated Pn travel-time curves for the Fennolora long-range profile in Scandinavia (Figure 2, top) (using the preliminary 3-D model, revision 2.2). These Figures show that observed Pn travel-times within the Baltic shield at shot points B and I fit Pn travel-times calculated for our 3-D model (revision 2.2) with r.m.s. 0.58 sec and 0.71 sec, respectively. Similar results were obtained for Pn travel-times along Early Rise long-range profiles in North America. The 3-D velocity models developed for North America (revision 5.0) and for Northern Eurasia (revision 2.0) were used to produce maps of SSSCs for IMS stations and other stations needed for the relocation experiments. Figure 5 (top) and Figure 5 (bottom) show, as an example, the SSSC maps calculated for Pn and Sn waves, respectively, for the TXAR IMS station. This station is located near the boundary between the tectonically active western regions of North America and the Pre-Cambrian platform. The SSSCs computed for Pn waves varied from +5 seconds to -5 seconds for western USA and the North American Pre-Cambrian platform, respectively. SSSC variations for Sn waves are more pronounced. SSSCs were calculated in Northern Eurasia only for Pn waves.

The purpose of relocation experiments in this work is to evaluate the influence of SSSCs for Pn, Pg, and Sn phases in North America and SSSCs for Pn waves in Northern Eurasia for regional seismic event locations. We tested location accuracy by using SSSCs inferred from the 3-D model along with the estimated modeling and measurement errors to relocate test events with known location and compare the results with locations based on the IASPEI-91 travel-times. Careful Pn travel-time and waveform analyses were performed to identify and eliminate outliers. The LocSAT program was used for seismic event relocation experiments. Results of relocation experiments for selected GT0 or GT2 events showed that application of SSSCs did not improve locations of outliers. Results of relocation experiments for 31 selected events with known location located in different regions of Northern Eurasia and North America clearly indicate that the 3-D model-derived SSSCs and estimated modeling errors improved location accuracy and decreased 90% error ellipse area.

CONCLUSIONS AND RECOMMENDATIONS

Northern Eurasia

1. Pn travel-times recorded from nuclear and large chemical explosions within western areas of Northern Eurasia were collected and carefully analyzed for IMS calibration. Pn travel-time anomalies were recorded and plotted.

2. A preliminary version of a 3-D crustal and upper mantle velocity model of Northern Eurasia (western areas) (version 2.0) was developed and evaluated by comparison of observed and calculated Pn travel-times.

3. SSSCs for the Pn phase were calculated for IMS stations and several additional stations up to distance 20 deg in Northern Eurasia using the 3-D crustal and upper mantle velocity model.

4. These SSSCs, along with estimated modeling and measurement errors, were used to relocate a set of nuclear and large chemical explosions detonated within western areas of Northern Eurasia and recorded at regional distances. Utilization of the SSSCs resulted in a substantial improvement in seismic event location accuracy and a significant decrease of error ellipse area in comparison with location based on the IASPEI-91 travel-time tables. Mean mislocations for nine nuclear and chemical explosions were decreased from 28.1 km to 9.3 km, and mean error ellipse area decreased from 6,512.3 km^2 to 1,284.3 km^2 using IASPEI-91 travel-times and SSSCs(3-D), respectively. The ground truth locations (GT) are inside the error ellipses at 90% confidence level for all of the calibration events for both using IASPEI-91 travel-times and SSSCs(3-D).

North America.

1. The application of SSSCs(3-D) with estimated modeling error for Pn, Pg, and Sn phases for the preliminary 3-D velocity model of North America derived in this study (version 5.0) led to a clear improvement in seismic event location accuracy and a substantial decrease in error ellipse area compared to locations based on the IASPEI-91 travel-times. For 100% of the calibration events relocated using SSSCs(3-D) for Pn phase only and for all selected test events relocated using Pn, Pg, and Sn phases the ground truth locations (GT) are inside the error ellipses calculated at 90% confidence level. This confirms that the 3-D model used for North America is able to predict travel time variations with high accuracy.

2. The average distance between true and calculated epicenters decreased using Pn waves only from 19.4 km (IASPEI-91 travel times) to 5.7 km (SSSCs(3-D) for all 12 events analyzed. Similar relocation experiments using SSSCs for Pn, Pg, and Sn phases for another set of 10 GT0 or GT2 events improved location accuracy from 25.9 km to 5.7 km on average and decreased mean 90% error ellipse area from 3,840 km^2 to 817 km^2 while preserving 100% coverage. The improvement in accuracy of epicenter locations and decrease of error ellipse areas while keeping true locations inside the computed error ellipses shows the promise of the 3-D crustal and upper mantle velocity model approach for regional seismic event locations.

3. The validation results obtained show that model-based SSSCs produce significantly improved location accuracies and reduced confidence ellipses in cases where it can be shown that analysis data are accurate.

In accordance with the Joint US/RF research program of the IMS seismic calibration, our main recommendations for North America and Northern Eurasia include:

North America:

- Continuation of collection, documentation and analysis of data relevant to the IMS calibration for Alaska, Canada, Greenland and neighboring oceanic regions with the aim of extending and improving the 3-D velocity model of North America;

- Continuation of relocation experiments using additional calibration events with known location and origin time;

Northern Eurasia:

- Extension of the work to Siberia, the Far East and southern regions of the former Soviet Union territory in Northern Eurasia;

- Continuation of collection, documentation and analysis of data relevant to the IMS calibration for Siberia, the Far East and southern regions of the former Soviet Union territory in Northern Eurasia;

- Continuation of work to improve the 3-D velocity model of Northern Eurasia;

- Calculation and validation of SSSCs for other regional phases: Sn, Pg, and Lg;

- Continuation of relocation experiments using additional calibration events with known location and origin time.

REFERENCES

Firbas, P., A.B. Peshkov, and V. Ryaboy. From IASP-91 global model to a 3-D model for CTBT monitoring. In: Upper Mantle Heterogeneities from Active and Passive Seismology (Edited by K. Fuchs), Kluwer, 199-214, 1997.

Firbas, P., Location calibration based on 3-D modeling. In: Advances in Seismic Event Location (Thurber, C.H. and Rabinovitz, N. - editors). Kluwer, 135-162. (2000, In print).

Kennett, B.L.N. (editor). IASPEI 1991 Seismological Tables, Australian National University, 167 p., 1991.

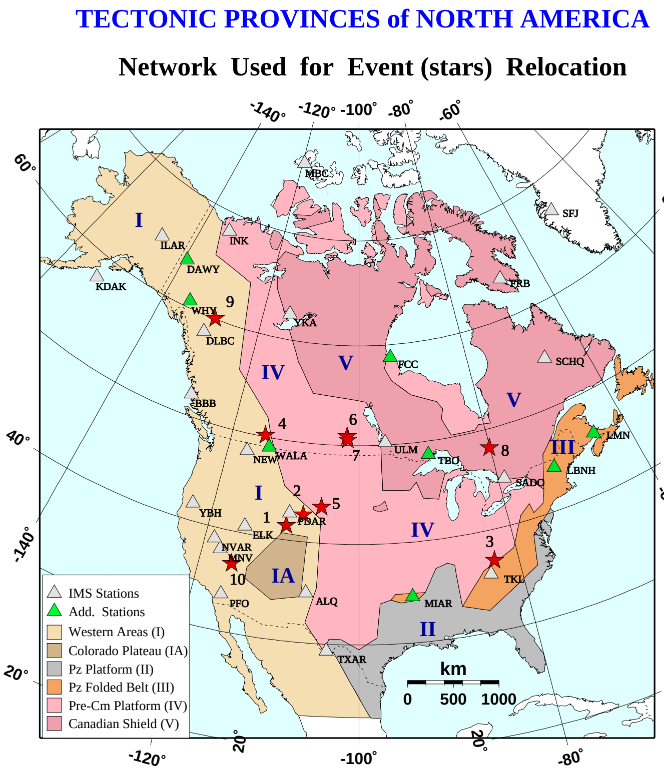
Kennett, B.L.N., E.R. Engdahl, and R. Buland, Constraints on seismic velocities in the Earth from traveltimes. Geophys. J. Int., 122, 108-124, 1995.

Pakiser, L.C., and Mooney, W.D., (editors), (1989), *Geophysical framework of the continental United States.* Geological Society of America, Memoir 172, 826 p.

Pavlenkova, N.I. (1996). *Crust and upper mantle structure in Northern Eurasia from seismic data.* Advances in geophysics, v. 37, Academic Press, 1-121.

Romanowicz, B.A.(1979), *Seismic structure of the upper mantle beneath the United States by three-dimensional inversion of body wave arrival times*, Geophys. J. R. Astr. Soc., *57*, 479-506.

van der Lee, S., and Nolet, G. (1997a), *Seismic image of the subducted trailing fragments of the Farallon plate*, Nature, vol. 386, 266-269.



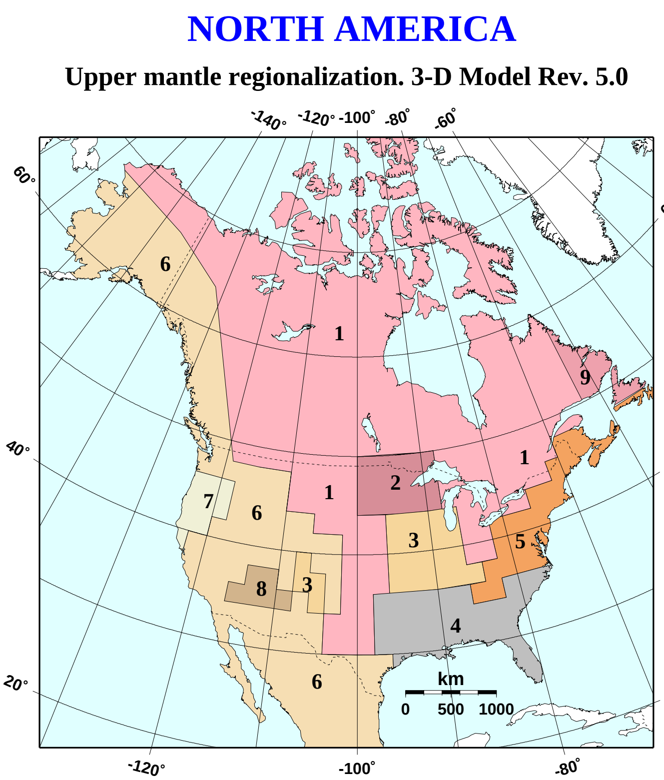
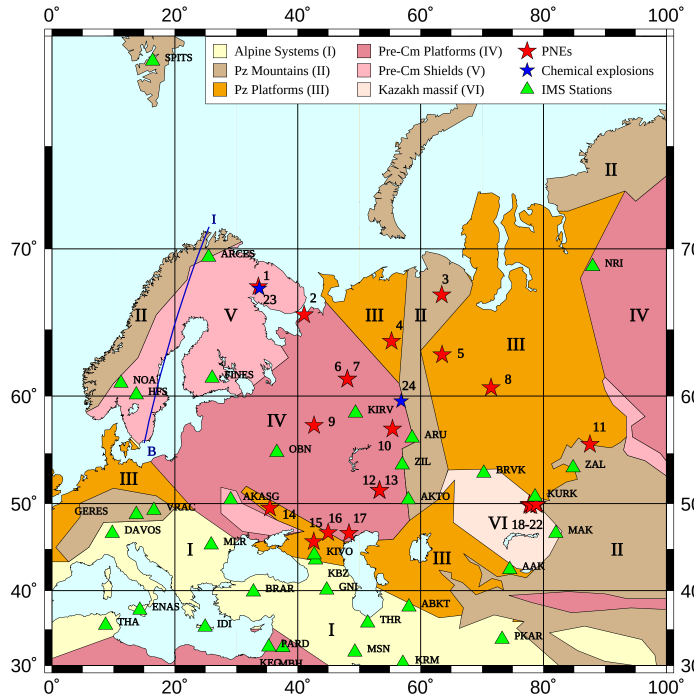


Figure 1. North America. Tectonic map and network used for relocation experiments (top) and upper mantle P-velocity regionalization (bottom). Stars are true locations of GT0 or GT2 events. Numbers on the regionalization map refer to numbers on the velocity models in Figure 3 (top).

NORTHERN EURASIA (western areas)

IMS Stations, Main Tectonic Provinces and Calibration Events Used



UPPER MANTLE REGIONALIZATION

Model (Rev. 2.0)

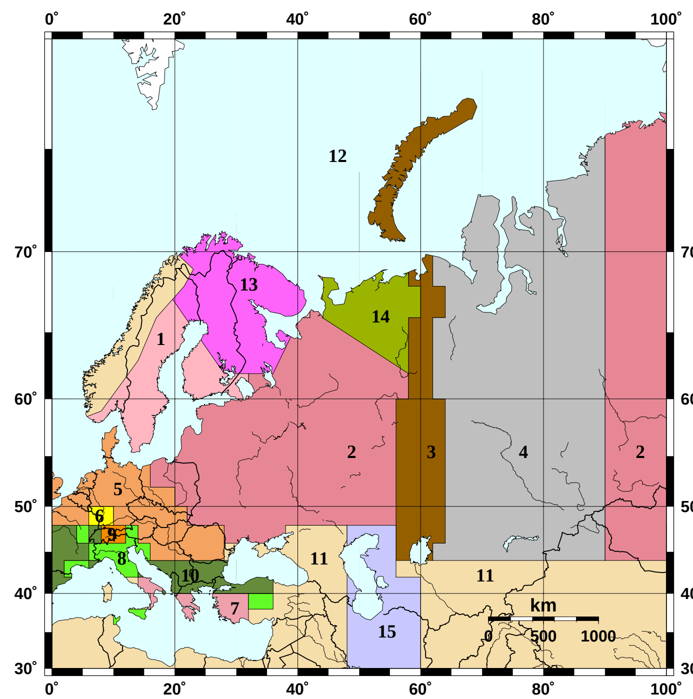
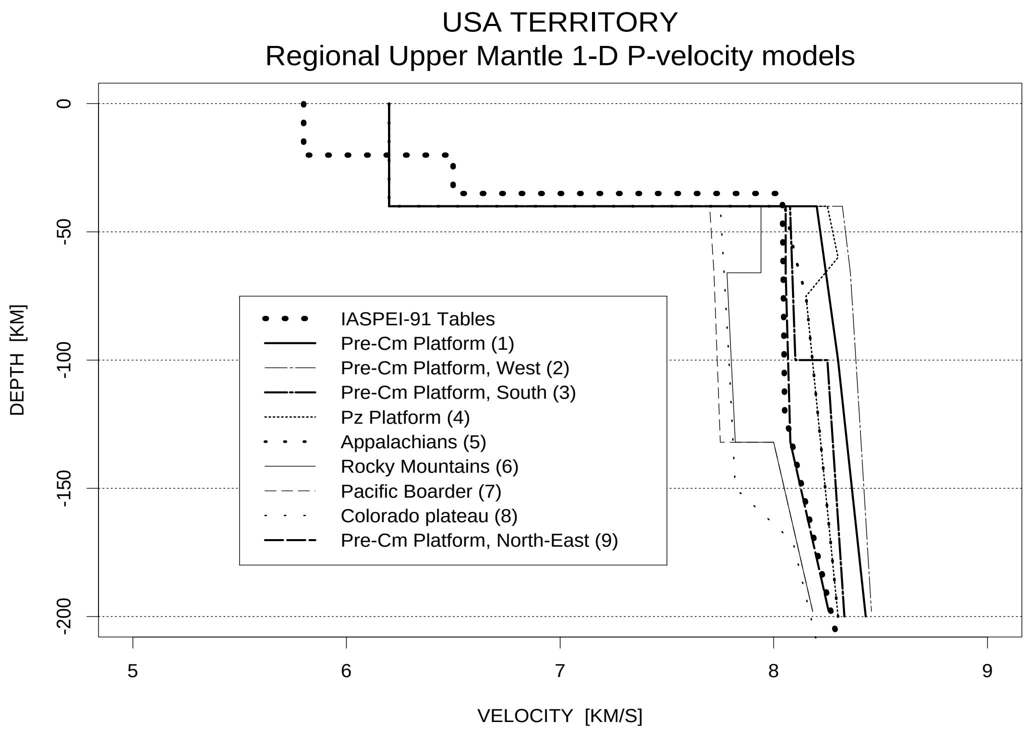


Figure 2. Western areas of Northern Eurasia. Tectonic map (top) and map of the upper mantle P-velocity regionalization. Stars are explosions used in this work. Numbers on the regionalization map (bottom) refer to numbers on the velocity models in Figure 3.



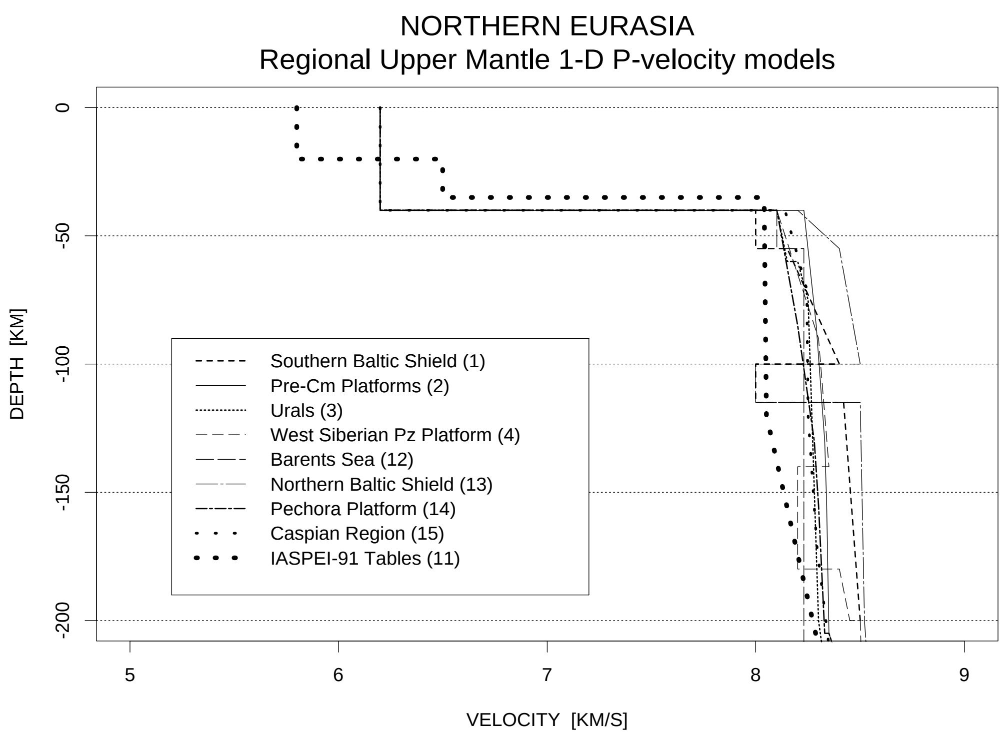
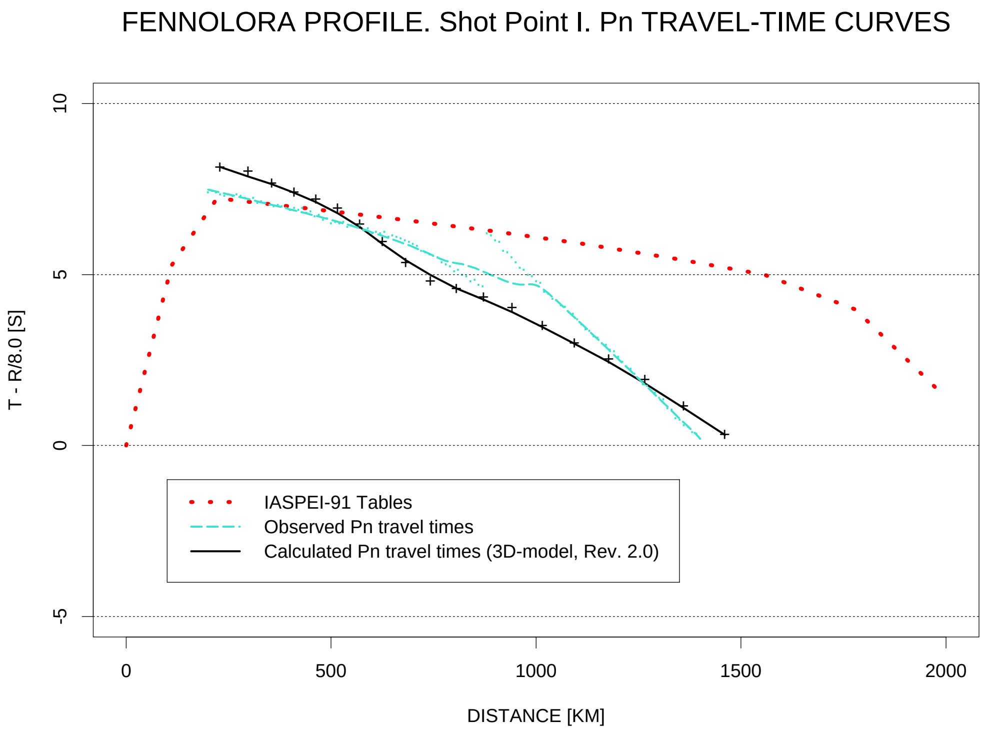


Figure 3. Regional upper mantle 1-D P-velocity models of North America (top) and Northern Eurasia (bottom).



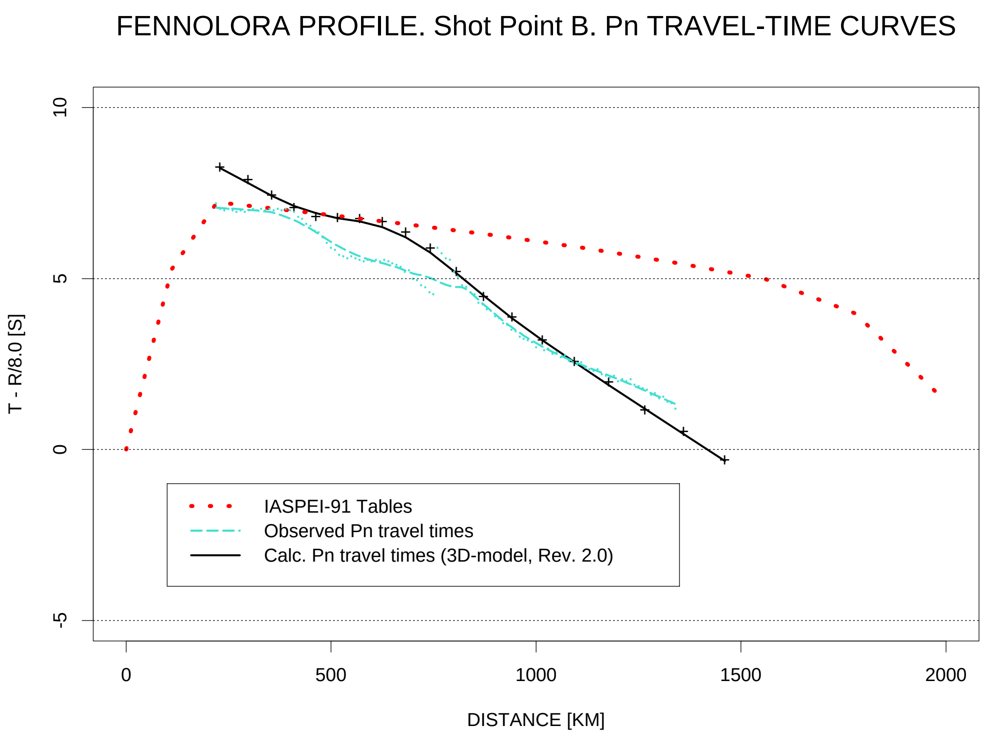


Figure 4. Baltic Shield. Comparison of observed and calculated Pn travel-time curves for 3-D model, revision 2.2, shot points I (top) and B (bottom) of the Fennolora profile. Shot points I and B are located on northern and southern ends of the Fennolora profile, respectively (Figure 2, top). Crosses are calculated Pn travel times. Dashed and solid lines are smoothed observed and calculated Pn travel-time curves, respectively.

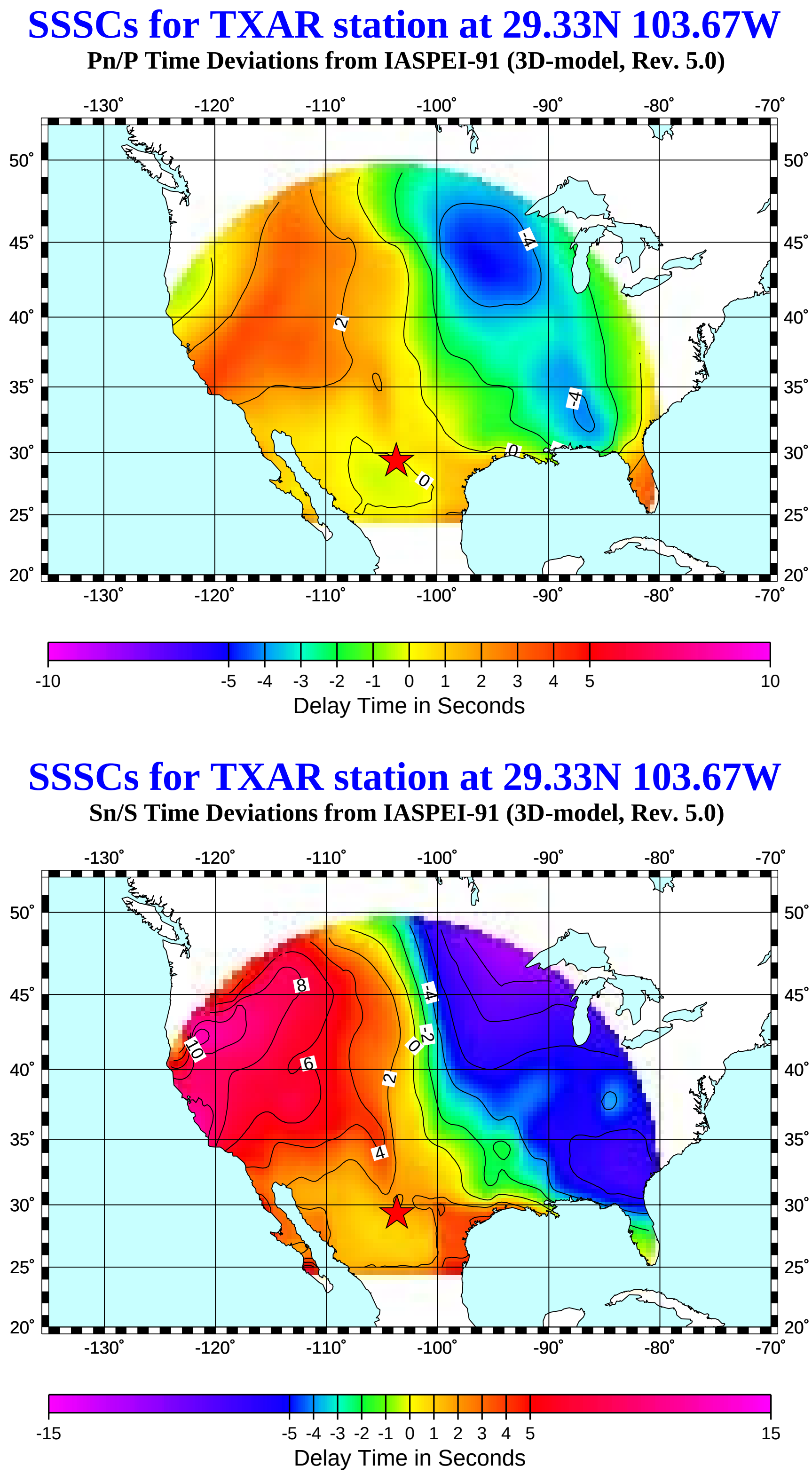


Figure 5. SSSCs calculated for Pn (top) and Sn (bottom) phases using 3-D model, revision 5.0, for the TAXAR station (star).